Application of semantic web ontologies for the improvement of information exchange in existing buildings

Farhad Sadeghineko
Glasgow Caledonian University, Glasgow, United Kingdom
Department of Construction and Surveying, farhad.sadeghineko@gcu.ac.uk

Bimal Kumar
Northumbria University, Newcastle, United Kingdom
Department of Architecture and Built Environment, bimal.kumar@northumbria.ac.uk

Abstract:
Facilitating the information exchange and interoperability between stakeholders during the life-cycle of an asset can be one of the fundamental necessities for developing an enhanced information exchange framework. Such a framework can also improve the successful accomplishment of building projects. In real-world building projects, the construction industry's information supply chain may initiate from near scratch when new building projects are started resulting in diverse data structures represented in unstructured data sources, like Excel spreadsheets and documents. Large-scale data generated throughout a building's life-cycle requires exchanging and processing during an asset's Operation and Maintenance (O&M) phase. Building information modelling (BIM) processes and related technologies can address some of the challenges and limitations of information exchange and interoperability within new building projects. However, the use of BIM in existing and retrofit assets has been hampered by the challenges surrounding the limitations of existing technologies. The aim of this paper is twofold. Firstly, it briefly outlines the framework previously developed for generating semantically enriched 3D retrofit models. Secondly, a framework is proposed focussing on facilitating the information exchange and interoperability for existing buildings. Semantic Web technologies and standards, such as Web Ontology Language and existing AEC domain ontologies are used to enhance and improve the proposed framework. The proposed framework is evaluated by implementing an example application and the Resource Description Framework data produced by the previously developed framework. The proposed approach makes a valuable contribution to the asset/facilities management (AM/FM) domain. It should be of interest to various FMpractices for existing assets, such as the building information/knowledge management for design, construction and O&M stages of an asset's life-cycle.

KEYWORDS:
Building Information Modelling (BIM), Industry Foundation Classes (IFC), Point Cloud Data (PCD), Resource Description Framework (RDF), Semantic Web technologies, Web Ontology Language (OWL), Information exchange and interoperability

1. Introduction and Background

The use of the BIM process has lately gained a lot of momentum within the Architecture, Engineering, and Construction (AEC) domain (Volk, Stengel, & Schultmann, 2014). In the construction industry, the BIM process has been adopted for various purposes, such as Asset/Facilities Management (AM/FM), renovation, and heritage restoration and preservation (Volk *et al.*, 2014; Barazzetti, 2016). The use of the BIM process is beneficial for improving different aspects of a building's life-cycle, such as the decision-making process and the precision of the design during the planning stage, quality of the product, management and exchange of information, energy efficiency, sustainability, and health and safety (Götz, Karlsson, & Yitmen, 2020; Hayne, Kumar, & Hare, 2014; Sadeghineko, Kumar, & Chan, 2018; Sheikhkhoshkar, Pour Rahimian, Kaveh, Hosseini, & Edwards, 2019). In terms of digitising the information involved in a building's life-cycle, BIM models are considered essential

https://doi.org/10.1108/CI-03-2021-0058

parts of a BIM process. The information embedded in BIM models is used throughout a BIM-enabled asset life-cycle to facilitate the performance of Operation and Maintenance (O&M) (Klein, Li, & Becerik-Gerber, 2012), exchange of information about a facility (Tang, Huber, Akinci, Lipman, & Lytle, 2010), and energy analysis and simulation (Wang, Cho, & Kim, 2015). BIM models are also used to facilitate the design visualisation of an asset, estimate material and costs, monitor an asset's condition, design and fabrication & prefabrication, and incorporating supplementary information and knowledge into BIM models. Moreover, the exchange – storing, sharing, and reusing – of information embedded in BIM models is vitally crucial for taking full advantage of models in a BIM-driven building project (Kumar, 2016).

While the BIM process has gained interest in new building projects, its use in existing and retrofit buildings has been hampered by the challenges and limitations of related technologies (Barazzetti, 2016; Thomson & Boehm, 2015). Different surveying technologies, such as image-based (e.g. Photogrammetry and Videogrammetry) and range-based (e.g. 3D Laser Scanning), are employed to collect the data of an asset in the form of images and three-dimensional point measurements, also known as Point Cloud Data (PCD) (Oliver, Seyedzadeh, Rahimian, Dawood, & Rodriguez, 2020). 3D laser scanning technology has been extensively used to collect geometrical data from existing buildings, and PCD is the output of this technology. PCD is exploited for various purposes like tracking & monitoring construction progress, capturing the actual as-built condition of a facility, health and safety on construction sites, energy efficiency, and generating parametric 3D models (Pour Rahimian, Seyedzadeh, Oliver, Rodriguez, & Dawood, 2020; Hayne *et al.*, 2014; Seyedzadeh, Rahimian, Oliver, Glesk, & Kumar, 2020).

In terms of a real-world practical approach for using PCD to generate building components, available commercial and open-source BIM-driven platforms are employed to manually carry out this process, which is considered a time-consuming, tedious, labour intensive, and error-prone process (Son & Kim, 2016). Hence, several studies have been undertaken to develop and propose approaches for changing the manual process of generating building models into an automated or semi-automated process. These approaches mainly aim to utilise PCD as the primary geometrical data source (Thomson & Boehm, 2015). This process is also known as the Scan-to-BIMs method. Technically, the result of such approaches is not a full-blown BIM model as usually understood (Volk *et al.*, 2014; Thomson & Boehm, 2015). The fact is that an appropriate parametric model that is fit for a BIM-based process of design, construction and O&M of assets should incorporate geometrical and non-geometrical data (Sadeghineko & Kumar, 2020; Volk *et al.*, 2014). One of the main reasons for generating a semantically enriched 3D model in a BIM-enabled project is improving and enhancing the information exchange and interoperability processes throughout the building's life cycle (Curry *et al.*, 2013). While the geometrical properties can be extracted from a PCD, non-geometrical data, such as O&M-related data (e.g. Residual Risks, Sustainability Performance, Expected Life, and Risks), may need to be combined with the 3D model for generating a genuinely semantically enriched 3D building model. In current practice, approaches proposed and developed in the literature mainly focus on the detection of geometries in PCD rather than the information required in BIM models (Volk *et al.*, 2014; Sadeghineko, Kumar, & Chan, 2019).

The Industry Foundation Classes (IFC) data model and the Construction Operation Building information exchange (COBie) data format are examples of practical information exchange standards within the AEC industry. COBie is a spreadsheet (.xlsx) data format that includes information about different aspects of an individual building, such as type, location, make, tag, serial number, and installation information of building elements. It is mainly used in AM/FM domains for O&M purposes and not for exchanging information between BIM-driven applications (Farias, Roxin, & Nicolle, 2015; Volk *et al.*, 2014). On the other hand, the IFC data model is an open-source data model developed by buildingSMART International (bSI). IFC can be considered the most well known and practical standard used for information exchange purposes between BIM-driven applications (Pauwels *et al.*, 2011; Kumar, 2016).However, due to some of the limitations and implications of the IFC data model (Uggla & Horemuz, 2018; Molinero Sánchez, Gómez-Blanco Pontes, & Rivas López, 2019) on capturing all kinds of non-geometrical data, commercial BIM software largely suffer from the limitations of exchanging data and indirectly capturing semantically enriched 3D models of existing assets. In real-world projects, the information that cannot be combined with the BIM models is inevitably stored in different data formats outside the model, which makes data manipulation, information exchange, and interoperability processes ineffective and inefficient (Sadeghineko & Kumar, 2020).

Various schemas like ifcOWL (Pauwels & Terkaj, 2016), ifcJSON (Afsari, Eastman, & Castro-Lacouture, 2017), and COBieOWL (Farias *et al.*, 2015) have been developed as a second alternative schema for distributing data on the Web effectively and efficiently by using semantic web technologies, in particular the Web Ontology Language (OWL). However, they are not designed to generate BIM models, and available BIM applications currently do not support such schemas (Sadeghineko & Kumar, 2020; Volk *et al.*, 2014). For example, ifcOWL is predominantly created from an existing IFC data model by converting IFC into OWL ontology by implementing the IFC-to-RDF (Pauwels *et al.*, 2011) and EXPRESS-to-OWL (Pauwels & Terkaj, 2016) algorithms. The process of developing such schemas mainly commences from a pre-designed or an existing building model, which may or may not incorporate all kinds of non-geometrical data. The generated ifcOWL may subsequently result in not incorporating non-geometrical data or perhaps data that IFC cannot handle or represent. Additionally, different ontologies like Building Topology Ontology (BOT) and Ontology for Managing Geometry (OMG) have recently been developed by World Wide Web Consortium (W3C) Linked Building Data Community Group (W3C LBDCG) for storing and sharing data on the web. BOT is a modular building ontology developed for expressing the topology of a building (e.g. Site, Building, Space, and Building Element), and OMG has been developed for facilitating the reuse of linked geometry descriptions of an object on the Web (Rasmussen, Pauwels, *et al.*, 2017; Terkaj, Schneider, & Pauwels, 2017).

An approach has been developed in Sadeghineko & Kumar, 2020 to address the challenges and limitations of generating BIM models from PCD. The proposed framework focuses on generating semantically enriched 3D retrofit models from PCD by utilising Resource Description Framework (RDF) as semantic web technology and standard. This paper outlines the proposed framework before proposing the approach for facilitating the information exchange for existing assets by utilising existing building ontologies. A procedure is proposed in this paper aiming to utilise the raw data presented in previously RDF data interlinked to the model as well as the existing ontologies within the AEC industry to generate the OWL version of the data, which incorporates all kinds of information required for maintenance purposes of new, existing and retrofit assets.

2. Related work

2.1. Parametric modelling utilising Point Cloud Data (PCD)

An existing building may not have a 3D as-designed model or indeed any model at all. In such cases, 2D drawings and paper-based or digital documents are the only available information sources for generating BIM models (Sadeghineko *et al.*, 2018, 2019). PCD, as the output of the 3D laser scanning technology, is widely used within the AEC domain for generating building models by utilising existing BIM applications to implement the process of converting PCD into 3D building models, which is mainly carried out manually. In terms of moving towards an automated process of mapping building models, the Scan-to-BIMs method is employed in various studies to generate 3D building components by using PCD data as the primary geometrical data source (Thomson & Boehm, 2015; Barazzetti, 2016). Moreover, several semi-automated approaches have been proposed in the literature to move from the traditional and manual process of generating parametric models towards an efficient and effective automated or semi-automated procedure. Geometrical attributes, such as linear, planar patches (surfaces), 3D primitives, and volumetric characteristics, are employed in proposed methods to develop semi-automated procedures with varying success (Thomson & Boehm, 2015; Tran, Khoshelham, Kealy, & Díaz-Vilariño, 2018). The Scan-to-BIMs process employed by studies is generally implemented through several common steps, viz. the collection of data in PCD, PCD registration, PCD segmentation, and the generation of building elements (Figure 1).

Concerning the proposed approaches, different data collection technologies, such as image- and range-based methods, are utilised to collect the data from existing buildings in the form of PCD. Different existing algorithms, such as unsupervised subspace learning technique, maximum likelihood estimation sample consolidation (MLESAC), single value decomposition (SVD) and α-shape algorithm, are employed to develop new approaches generating building elements from PCD. A segmentation algorithm declared based on the unsupervised subspace technique can retrieve linear relationships between elements in PCD. This technique is mainly employed to identify the number of linear relationships, associated dimensions, and segmentation groups of points in PCD. The MLESAC and SVD methods are implemented to calculate and extract primary geometries from the PCD, and the α-shape algorithm is predominantly used to extract the corresponding planar patches (surfaces). Other exist-

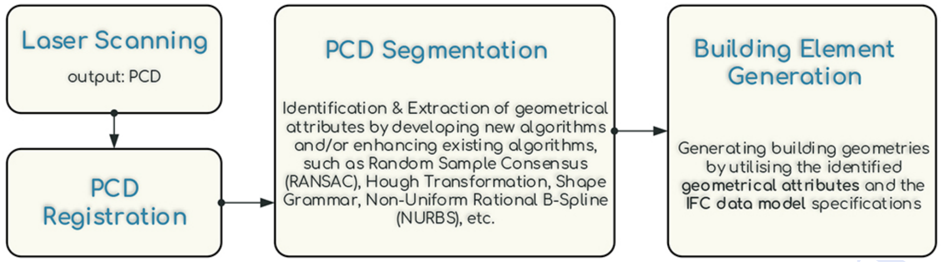

Fig. 1: The general process of capturing building elements from PCD, also known as Scan-to-BIMs.

ing algorithms, such as Region Growing Plane Segmentation (RGPS), Random Sample Consensus (RANSAC), Contour Filtration, and Hogh Transform, are also used to detect and extract geometrical data corresponding to their building elements through the PCD segmentation process. The work presented in Zhang, Vela, Karasev, & Brilakis, 2015 could be an example of using existing algorithms to propose an approach to reconstruct different building elements from real-world projects. The main focus is on identifying planar surfaces in the PCD due to the importance of planar patches in shaping 3D geometries and primitives (Dore & Murphy, 2015). Another example of generating building elements through the Scan-to-BIMs process can be the work undertaken by Thomson & Boehm, 2015 aiming to document 3D building components like walls, floors, and ceilings. The PCD segmentation process is implemented through an enhanced RANSAC algorithm, which detects planes and surfaces related to building components. The geometrical attributes, such as coordinate, width, and length, are employed to construct the basic IFC entities for identified elements. The created IFC data model is then used to visualise the 3D building geometries.

In contrast to using the Scan-to-BIMs process in new and existing buildings, its use has also gained interest in retrofit and historical buildings. A variety of approaches have been proposed and developed for reconstructing historical building components by using PCD as the primary geometrical data source (Banfi, Chow, Ortiz, Ouimet, & Fai, 2018; Quattrini, Malinverni, Clini, Nespeca, & Orlietti, 2015). Banfi *et al.*, 2018 proposed a semi-automated approach that integrates advanced spatial modelling and NURBs techniques for converting spatial data of 3D building components in a historical environment gathered by modern geometrical survey technologies like 3D laser scanning and Photogrammetry (Pour Rahimian *et al.*, 2020). PCD as the primary geometrical data source, CAD drawings and information presented in paper-based documents, and NURBs-based algorithms are integrated into BIM-enabled applications to generate building components with a high level of geometrical accuracy. Existing modelling applications (commercial BIM platforms) are adopted to extract geometrical data from PCD by exploiting NURBs interpolation procedure. Surfaces related to their corresponding building elements are first identified based on NURBs features and then employed to generate the 3D building models in BIM-driven applications through a manual process.

The fact is that the final results of approaches proposed based on the Scan-to-BIMs method are simple shapes or primitives that only contain geometrical data, such as length, width, area, and volume. However, as mentioned previously, the non-geometrical data needs to be combined with the 3D building geometries through a manual process by either converting 3D geometries into building types (building elements/objects) where the non-geometrical data can be attached to the model or creating new building components based on the model specifications.

2.2. Information exchange within the AEC industry

One of the main reasons behind BIM-driven project delivery in the AEC industry is storing, sharing, and reusing information in standard formats to improve the information exchange processes (Beetz & Borrmann, 2018; Kumar, 2016). One of the challenges in the AEC industry is the communication between different BIM platforms which directly impacts the information interoperability performance (Pauwels *et al.*, 2011). Hence, several open data exchange formats and schemas have been developed within the AEC domain to represent the construction data and enhance communications between modelling applications, including participants involved in building projects. The IFC data model and COBie data are well-known and practical examples of data exchange stan-

https://doi.org/10.1108/CI-03-2021-0058

dards within the AEC industry. IFC is an open-source standard globally used to describe, share and exchange construction and limited facilities management information between diverse BIM-driven software applications. COBie is an international data exchange standard predominantly used in AM & FM domains for information interoperability and O&M purposes (Shalabi & Turkan, 2016; Volk *et al.*, 2014).

However, the existing information exchange standards and formats also show limitations for certain functionalities. For example, COBie is essentially a non-geometrical data source mainly used to share information about different aspects of an individual building in Excel spreadsheets. COBie cannot be utilised in BIM-driven applications for generating BIM models as it cannot transfer geometries (Farias *et al.*, 2015; Gui, Wang, Qiu, Gui, & Deconinck, 2019). On the other hand, the IFC data model cannot present all kinds of non-geometrical data involved in BIM models (Sadeghineko *et al.*, 2019; Sadeghineko & Kumar, 2020). In this regard, commercial BIM applications largely suffer from the limitations of exchanging data and indirectly capturing 3D models of buildings, particularly existing assets that do not have an appropriate model. Hence, some of the information that cannot be presented through existing information exchange standards and formats is inevitably stored in different file formats outside the model, such as PDF, 2D paper-based CAD drawings, and Excel spreadsheets (Sadeghineko & Kumar, 2020).

Semantic Web technologies and standards like web-based ontologies have gained notable interest within the AEC and AM/FM for information exchange, interoperability, and management. Concerning the challenges and limitations of existing information exchange standards, studies have been undertaken to improve existing information exchange standards and tools by utilising Semantic Web technologies as a feasible solution. Some of the examples of these are the ontology for IFC, also known as ifcOWL (ifc Web Ontology Language) (Pauwels & Terkaj, 2016), an ontology for COBie (COBieOWL) (Farias *et al.*, 2015), and ifcJSON (ifc JavaScript Object Notation) (Afsari *et al.*, 2017). The main idea behind developing such schemas is to use existing information about a building and convert it into OWL ontologies, predominantly used to store and share the information on the Web. While some of the studies focus on using Semantic Web technologies and standards to improve existing data exchange tools, others focus on developing web-based ontologies to describe construction-related information. The Building Topology Ontology (BOT), Ontology for Managing Geometry (OMG), Building Product Ontology (BPO), and Bridge Topology Ontology (BROT) are examples of such ontologies.

2.3. *Web-based ontologies for buildings*

Studies have proposed web-based schemas by utilising Semantic Web technologies and standards to improve existing information exchange standards and tools. As mentioned previously, ifcOWL, ifcJSON, and COBieOWL are examples of such schemas. Concerning the ifcOWL schema, the first conversion of the IFC schema into OWL was initially proposed by Schevers & Drogemuller, 2005. IFC data model specifications were used as a reference example for highlighting and addressing some of the key issues of information exchange and interoperability within AEC. Beetz, Van Leeuwen, & De Vries, 2009 proposed a semi-automated approach to convert IFC-EXPRESS into OWL (ifcOWL) to enhance the IFC data model applicability and reusability. Thenceforward, studies have been carried out proposing Web Ontology versions of different IFC formats like the OntoSTEP (Standard for the Exchange of Product data model Ontology) version proposed by Barbau *et al.*, 2012. However, there was a lack of formalisation and standardisation in proposed ontologies. Hence, a more usable and recommendable version of ifcOWL was developed by Pauwels & Terkaj, 2016. The current version of ifcOWL is initially developed by implementing IFC-to-RDF (Pauwels *et al.*, 2011) and EXPRESS-to-OWL (Pauwels & Terkaj, 2016) procedures. The main idea behind creating ifcOWL was to continue using the IFC standard to represent building data and take advantage of Semantic Web technologies to distribute, extensibility, and reasoning of data (Pauwels & Terkaj, 2016). However, despite the improvement made to the original IFC data model through Semantic Web technologies, ifcOWL also shows limitations in real-world project usage. As stated in Terkaj & Pauwels, 2017, "*the resulting ifcOWL is a large monolithic ontology that presents serious limitations for real industrial applications in terms of usability and performance (i.e. querying and reasoning)*". In addition to that, in contrast to the original IFC data model, ifcOWL cannot be used as an information exchange standard for communication purposes between BIM-driven applications as they do not support such schemas.

Another example of Semantic Web-based schema created for the IFC data model is the work presented in Afsari *et al.*, 2017. The proposed method main objective is to provide the JSON (JavaScript Object Notation) representation of the IFC specification. Like the ifcOWL, ifcJSON uses the EXPRESS schema to present existing IFC data model schema entities generated for an individual building project in JSON syntax. The study carried out by Farias *et al.*, 2015 proposes a semi-automated approach for creating the COBieOWL ontology by using the data presented in COBie spreadsheets. The generated COBieOWL is first serialised into RDF Turtle format and then edited in Protégé OWL editor before populating the data. The SPARQL (Simple Protocol And RDF Query Language) is employed in the Protégé platform to manage and manipulate the data presented in COBieOWL. In terms of generating building models using the developed schemas, as mentioned previously, COBie is only used for information delivery of an individual asset for maintenance purposes within the FM domain. It cannot be used for generating models within BIM platforms. Moreover, the developed schemas mainly focus on using integrated information exchange standards and Semantic Web technologies to produce shareable data, which can be a feasible solution to the information exchange and interoperability limitations. However, the data used for implementing such schemas is extracted from an existing model. The model employed for creating shareable information may or may not incorporate all kinds of data required for different sectors of a BIM process (Sadeghineko & Kumar, 2020).

Contrary to the proposed and developed web-based schemas, other studies focus on developing Web Ontologies to represent structured building data on the Web, which also can be used as Linked Data (LD) or Linked Open Data (LOD). In current practice, the exchange of information and its description come with different data formats, and the communication between them is predominantly through diverse file formats with an implicit relationship between them (Pauwels, McGlinn, Törmä, & Beetz, 2018). However, LD/LOD concepts can be a feasible solution to the limitations that hamper appropriate communication between diverse data sources within the AEC industry. The main idea behind the LD/LOD is to use Semantic Web technologies and combine data distributed in different data formats to enhance data interoperability, reasoning and querying (Lee, Chi, Wang, Wang, & Park, 2016). Moreover, LD is a web-centric approach that provides a mechanism for gathering heterogeneous data formats and presenting them in a homogeneous format. LD uses Semantic Web standards like RDF and OWL as its main structure, i.e. any type and format of data can be combined with LD from other domains as long as they use linked data standards (Curry *et al.*, 2013). In other words, any data format (e.g., PDF, Excel spreadsheet, and DWG) that needs to be used as LD requires to be converted into RDF and/or OWL before it is linked to LD/LOD. Nevertheless, studies have recently been carried out proposing minimal Web ontologies, such as BOT, OMG, BROT, and BPO, for describing building data on the Web or as LD.

2.4. AEC domain ontologies

The Building Topology Ontology (BOT) as a minimal ontology was initially proposed and developed by W3C LBDCG. The general idea behind the creation of BOT ontology was to define the relationships between the sub-components of a building in a clear and detailed manner. It also aims to provide the method for representing and reusing information within the AEC industry in the form of interlinked data (Bonduel, Oraskari, Pauwels, Vergauwen, & Klein, 2018). The first version of BOT ontology was initially proposed in Rasmussen, Hviid, & Karlshøj, 2017, and an updated version of this ontology was presented in Rasmussen, Pauwels, *et al.*, 2017, introducing changes applied to the initial version of BOT. Moreover, the definition of terms used in BOT ontology is identified by URIs (Uniform Resource Identifiers) in the BOT namespace (http://w3id.org/bot#). The prefix bot: is the shortened version of the BOT namespace (@prefix bot: <http://w3id.org/bot#>). The current version of BOT encompasses seven classes (e.g., bot:Zone, bot:Site, bot:Building, etc.), fourteen object properties (e.g., bot:containsZone, bot:hasBuilding, etc.), and one data property (bot:hasSimple3DModel). BOT documentation can be accessed through its IRI (Internationalised Resource Identifier) – http://w3id.org/bot. In addition, the building product, related properties and geometry ontologies are considered as the sub-groups of BOT ontology which is considered as the central and modular ontology. In other words, BOT ontology can be extended by other domain ontologies (Pauwels, McGlinn, *et al.*, 2018). It can be used in combination with other ontologies representing building product information, sensor data used for observations, data extracted from IoT (Internet of Things) devices, complex geometry of building components, and project management data.

The Ontology for Managing Geometry (OMG) was initially proposed in 2019 by Wagner, Bonduel, Pauwels, & Uwe, 2019 to describe geometries related to building elements. In other words, OMG ontology focuses on providing the means for linking building objects data to their corresponding geometry descriptions. The OMG ontology documentation can be accessed through its IRI – http://w3id.org/omg. The URIs identify the terms

https://doi.org/10.1108/CI-03-2021-0058

in OMG ontology in the OMG namespace (http://w3id.org/omg#). Concerning the OMG specifications, an object can be linked to its geometry description through three modelling complexity levels with different levels of functionalities associated with each level. Level 1 provides the means for connecting objects to their geometry descriptions directly. Level 2 of OMG introduces additional functionalities to the model, viz. handling of multiple geometry descriptions of the same objects, adding metadata to the model, and modelling dependencies between geometries. The geometry states as additional functionality, i.e. the version history of the description of geometries, can be included in the model through the use of Level 3 of OMG ontology.

The Building Product Ontology (BPO) (Wagner & Rüppel, 2019) is a minimal ontology designed for describing some of the non-geometrical data, predominantly assembly structures, relationships and connections between product components, properties, and property values, related to their corresponding building products and elements. However, BPO ontology does not support the representation of geometrical descriptions and material compositions of building products. BPO contains several classes, object properties, and data types utilised to represent building product descriptions like other ontologies. More information about BPO documentation can be found through its IRI – http://www.w3id.org/bpo. In terms of the topological and geometrical representation of building products, BPO can be extended and combined with BOT, OMG, and other ontologies to enhance the information exchange process about building projects. Several other ontologies are also available within the AEC domain, which can be used to represent different building-related data, like Smart Energy Aware Systems (SEAS) ontology.

Other core ontologies within the AEC domain focus on different types of constructions such as bridges, smart buildings, and cities (Sayah, Kazar, Lejdel, Laouid, & Ghenabzia, 2020). For example, the Bridge Topology Ontology (BROT) is a core ontology for defining the bridge constructions, including aggregated zones and components and their topological relations. The BROT ontology is designed and structured based on a generic modelling approach, and therefore, it can be applied to any type of bridge construction (Hamdan & Kozak, 2019). Another example for such ontologies could be the Web ontology for smart buildings, also known as SBOnto (Ontology for Smart Building), proposed by Žáček & Janošek, 2017 with the focus on formalising knowledge in smart buildings. However, BOT, OMG, and BPO ontologies are specifically used to extend the ontology created in this paper, described in the following sections.

3. Research Methodology

The research gap, challenges and limitations involved in generating semantically enriched parametric models and the information interoperability (information exchange tools and standards) within the AEC industry were investigated by reviewing academic journals, conference proceedings, books, and applied application (e.g. reports, buildingSMART, openBIM, RDF core and associated APIs) that contribute to the implementation of BIM for new buildings and retrofit assets. The focus was on three key subjects, viz. 1) The BIM process and its use in the construction industry, along with associated applications used in new, existing and retrofit buildings for generating parametric models, 2) Technologies and applications related to information exchange and interoperability tools and standards (e.g., IFC data model), and 3) Web-based technologies, such as Semantic Web technologies and standards (e.g., RDF, RDFS, OWL, and existing ontologies) relating to the management of the large-scale information involved in building projects.

The IFC data model as a well-known and commonly utilised information exchange standard within the AEC domain was investigated to identify its limitations and capabilities in handling all kinds of data. The Semantic Web technologies and standards were investigated to identify an appropriate standard format useful for managing the large-scale information embedded in building models. The existing Web ontologies were also investigated to identify their capabilities, applicabilities, and scalabilities. A combination of these technologies and tools was then adopted to enhance an existing framework (see Section 4) and expand it to improve and facilitate the information exchange and interoperability within the building projects. The extended framework is discussed in detail in Section 5.

4. A framework for generating semantically enriched retrofit 3D models using RDF

An appropriate parametric model that fits the BIM process of design, construction and O&M of buildings should incorporate geometrical and non-geometrical data. In current practice, the model generated from PCD initially contains only geometrical data. The non-geometrical data is combined with the building geometries to capture BIM objects that incorporate both data types. BIM applications and related standards and tools like IFC are not capable of representing all kinds of data. Due to these limitations, data is stored in different data formats, making data manipulation, management, and information exchange and interoperability inefficient and difficult. Hence, a framework has been developed in Sadeghineko & Kumar, 2020, which focuses on addressing the challenges and limitations involved in generating semantically enriched 3D retrofit models. As shown in Figure 2, the framework consists of three key steps, viz. 1) data collection, 2) data processing and 3) BIM models generation.

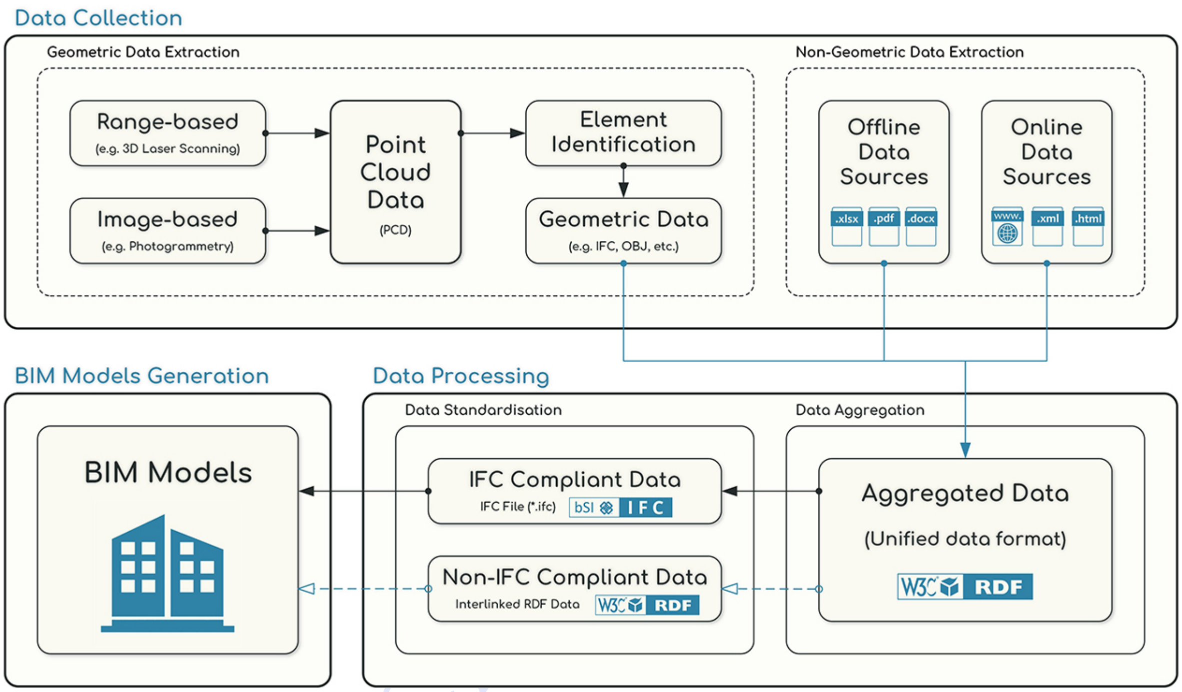

Fig. 2: A framework for generating semantically enriched 3D retrofit models developed by Sadeghineko & Kumar (2020).

The data collection step focuses on gathering geometrical and non-geometrical data. The geometrical data such as Cartesian points (coordinates) and geometric properties (e.g., length, width, and height) are extracted from the geometries identified in PCD. Offline and online data sources are also used to collect non-geometrical data. The non-geometrical data are practically stored as offline and online data in different formats. These data sources are used to retrieve the required non-geometrical data presented in different data formats. In the data processing step, the collected data is first aggregated into a unified data format. The Resource Description Framework (RDF) as a Semantic Web standard and technology is employed as the unified data format to aggregate data collected from distributed data sources. Data presented in RDF is classified into two different sections, viz. IFC and Non-IFC Compliant Data.

As the commonly used standard tool for exchanging building information within the construction industry, the IFC data model cannot handle all kinds of non-geometrical data. Hence, the first section includes data compliant with IFC specifications and is combined with the building models using the IFC schema. The latter section, predominantly containing a considerable portion of non-geometrical data, cannot be combined with building models due to the IFC limitations. This portion of data remains in the form of RDF data which is interlinked with the model. An RDF statement structure is based on three parts: triples, including a subject, predicate, and object. The subject and predicate are declared as URIs, where the object can be declared either as a URI or

https://doi.org/10.1108/CI-03-2021-0058

a literal value. URIs provided in the model are used as links to the information associated with BIM objects. Moreover, non-IFC-compliant data can be accessed through these links by importing the IFC file into any BIM platform that supports this format or opening the model generated from the IFC file in BIM applications such as Revit, BIM 360, and Autodesk A360 platforms. Implementing an RDF-TO-IFC algorithm carries out the process of generating semantically enriched 3D retrofit models from RDF data.

Furthermore, in terms of scalability and replicability, the developed framework is not limited to a specific building and can be applied to any building type, including new, existing and retrofit assets. The geometrical and non-geometrical data of an existing building was used to validate the process of the framework. The building project includes multiple wall components, slabs, door and window openings distributed in two floor plans. RDF data generated for each building element was employed to implement the RDF-TO-IFC algorithm for creating the IFC file. The IFC file was then used to generate building components (BIM objects) in BIM applications that support this format. Figure 3 illustrates the generated model opened in Autodesk BIM 360 web platform and the RDF data links associated with their corresponding building objects. These links are utilised as linked data to access the information related to each component. Figure 3 also shows the data related to a wall object presented on the web accessed via the live links embedded in the model. One of the major advantages of the developed framework is that all kinds of data, including geometrical and non-geometrical data, can be combined with the model as interlinked data, and the RDF data can also be used for further data processing purposes. Moreover, geometrical and non-geometrical data availability in a standard and unified data format improves the information exchange and interoperability in BIM-enabled projects.

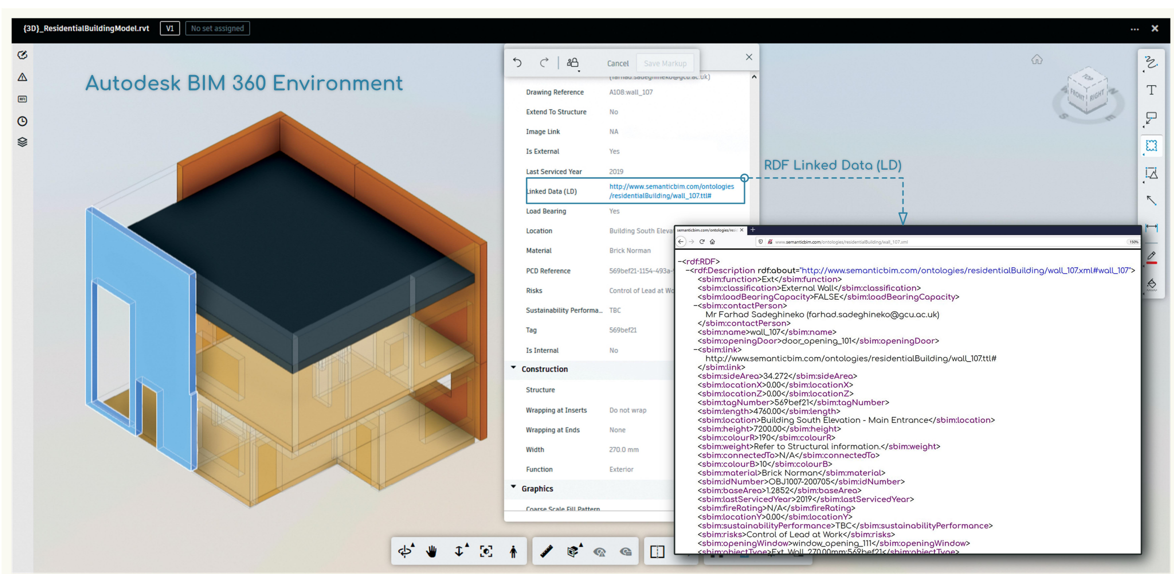

Fig. 3: BIM model opened in Autodesk BIM 360 environment, and links that are appended to the model to access data associated with building objects.

5. A framework for facilitating information exchange in existing buildings

In real-world building projects, the construction industry's information supply chain may initiate from near scratch when new building projects are started resulting in diverse data structures represented in unstructured data sources, like Excel spreadsheets and documents. A vast amount of information is generated throughout the project life span, which requires exchanging and processing during the O&M phase of an asset. Hence, facilitating the project data exchange process over its entire life-cycle between stakeholders can be considered one of the fundamental necessities for developing an enhanced information exchange and interoperability framework, which subsequently can improve the successful accomplishment of building projects. It is also essential to ensure that information delivery is at its best within the AEC industry (Seyedzadeh, Rahimian, Glesk, & Kakaee, 2017).

https://doi.org/10.1108/CI-03-2021-0058

The BIM process is widely adopted within the AEC industry to address some of the challenges and limitations of information exchange and interoperability. However, while the use of BIM processes can rectify some of these limitations in new building projects, its use in existing and retrofit assets has been hampered by the challenges surrounding the limitations of existing technologies in capturing retrofit building models, which is considered a challenging task in implementing BIM and managing large-scale data produced during the life-cycle of retrofit assets.

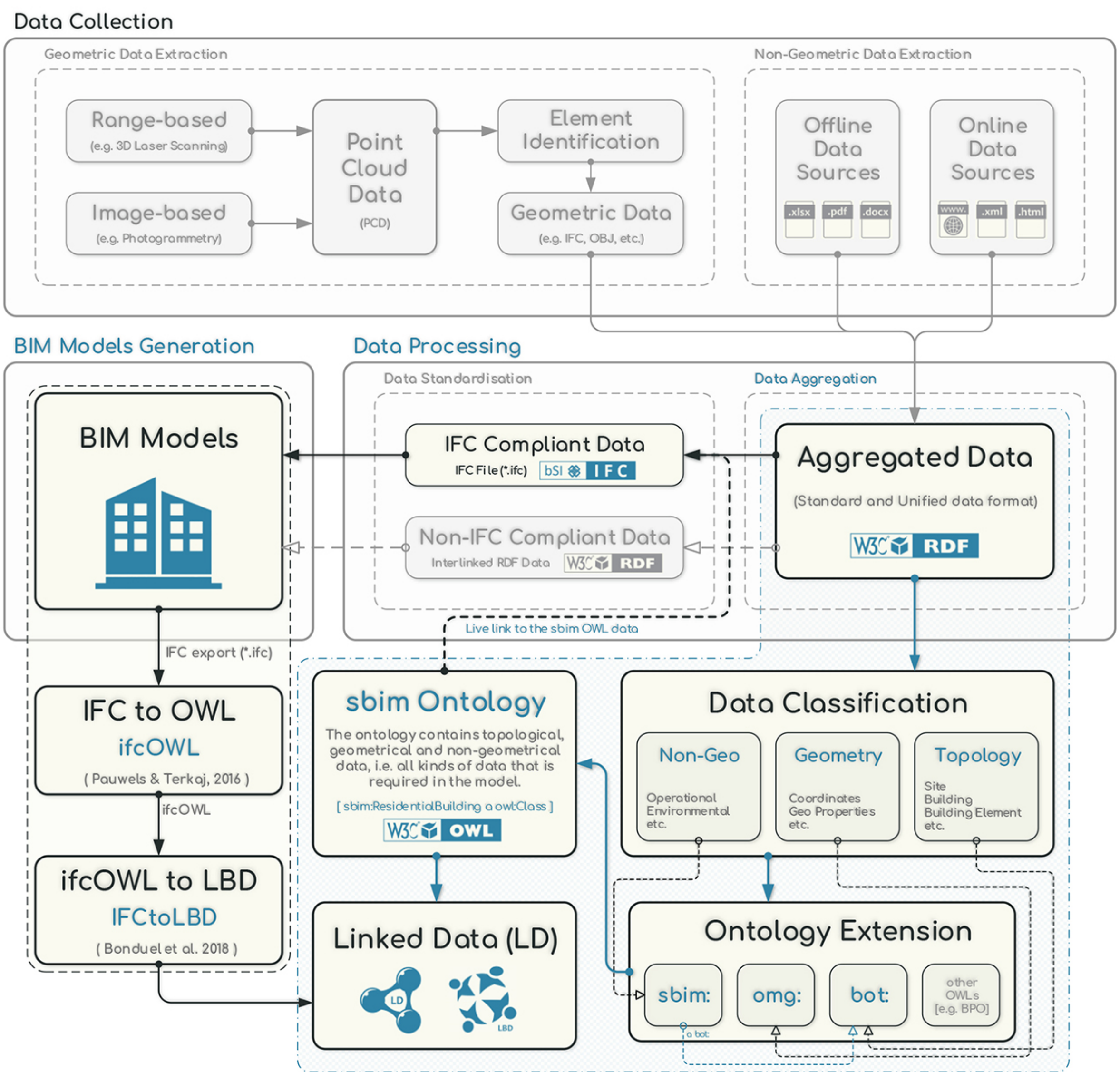

Fig. 4: The Proposed framework for facilitating information exchange and interoperability for existing assets.

The recent use of Semantic Web standards and technologies, in particular OWL, for exchanging information purposes has shown capabilities for providing feasible solutions to AEC's information exchange challenges and limitations. Furthermore, using LD principles in designing frameworks that involve data exchange can improve the information exchange process between interdisciplinary stakeholders in building projects and combining distributed data sources presented in different formats. Hence, this paper aims to adopt web-based principles to improve and enhance the framework initially developed for generating 3D retrofit models for existing buildings using RDF data. The framework outlined in the previous section was instigated by a partnership between Historic Environment Scotland (HES) and the authors' institution (Sadeghineko & Kumar, 2020). The HES BIM project specifications were initially investigated to classify the information used for structuring the RDF data for building

https://doi.org/10.1108/CI-03-2021-0058

components. RDF was employed as the unified and single standard format due to its reliability of handling all kinds of data (geometrical & non-geometrical), which is an important aspect of the information exchange and interoperability process in O&M of assets. Moreover, RDF specifications applicability was utilised to create RDF graphs related to their corresponding building components, such as site, building, building storey, floor slabs, internal & external walls, and openings.

However, this paper proposes an approach that aims to use the RDF data generated by the previously developed framework first to enhance the process of the framework developed in Sadeghineko & Kumar, 2020 (Figure 2) by adding more capabilities to it and second to improve the facilitation of information exchange and interoperability for exiting and retrofit assets by using Semantic Web technologies & standards and existing ontologies within AEC domain. The workflow of the enhanced framework is illustrated in Figure 4. Grayscale sections represent some of the framework steps developed for generating semantically enriched 3D retrofit building models (Figure 2). The coloured sections represent the extended part of the framework proposed to facilitate and improve information exchange and interoperability.

The first step of the extended framework concerns the data classification process (Figure 5). The HES BIM project specifications were initially utilised to distribute data into their corresponding classifications: identity, architectural, structural, spatial, environmental, and operational. An object-based approach was adopted to create RDF data for each building component. Moreover, the RDF data created for a building component (e.g., site, wall, and floor) contains data associated with the above categories. The main reason for employing such a classification approach was simplifying the translation process from RDF into IFC and gathering all kinds of information related to individual building components into a single & unified data format (Sadeghineko & Kumar, 2020). Hence, an ontology-based data classification process is implemented to distribute data into their related categorisations, viz, Non-geometrical (Non-Geo), geometrical (Geo), and topological (Figure 5). The geometrical category contains any data type associated with geometrical properties and attributes, such as coordinates, length, and width. The topological category consists of data associated with the spatial relationships between building elements, e.g., the relationship between a building and its components. The remaining data that do not fit into geometrical and topological categories are included in the non-geometrical classification.

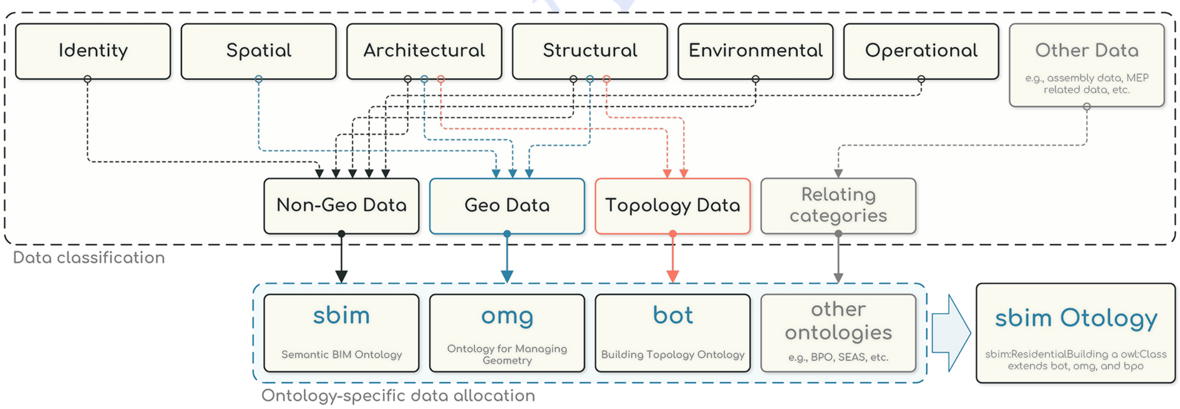

Fig. 5: Data classification and ontology-based data allocation processes.

The next step in the proposed framework is to allocate categorised data to their corresponding ontology-specific data types. As previously mentioned, several web ontologies are created within the AEC domain for different purposes, such as the spatial relationship between building elements (Rasmussen, Hviid, & Karlshøj, 2017), the presentation of geometrical data (Wagner *et al.*, 2019), and the assembly of building components (Wagner & Rüppel, 2019). The existing BOT, OMG, and BPO ontologies are used to extend the base ontology. These existing ontologies represent the data supported by their specifications, and the base ontology presents the remaining data. The BOT specifications are employed to present data categorised as topology related data, i.e., topological relationships between building elements. The OMG is designed to describe geometrical data related to their corresponding objects. Hence, this ontology is utilised to represent geometrical properties and attributes of building components. The BPO is also used to extend the base ontology to represent and describe building elements assembly and structure. The output of the ontology-specific data allocation process is the sbim ontology which contains all kinds of data.

As illustrated in Figure 4, the generated ontology is then combined with the model through the IFC specifications used to generate building models by importing the IFC file into any BIM-driven platforms that support the IFC format. Furthermore, the data is populated on the web and is also used as linked data within the model and can be accessed through the live link provided in the model (Figure 6). One of the advantages of using web-based ontologies and structured data based on the LD disciplines is that existing ontologies can extend the base ontology to represent large-scale data involved in the building industry. The ontology-based data generated by the proposed framework has LD principles as its structure and can be used as LD/LOD. The information embedded in the model can also be exported as IFC, and the existing algorithms can be used to convert IFC into ifcOWL and Linked Building Data (LBD). However, some of the information, such as the links to the web-based data combined with the models, will be lost when exported as IFC due to the IFC data model limitations, specifying that the ifcOWL and LBD data will not contain all the data initially combined with the models by implementing the framework. The ifcOWL limitations and implications are discussed in Section 6 of this paper.

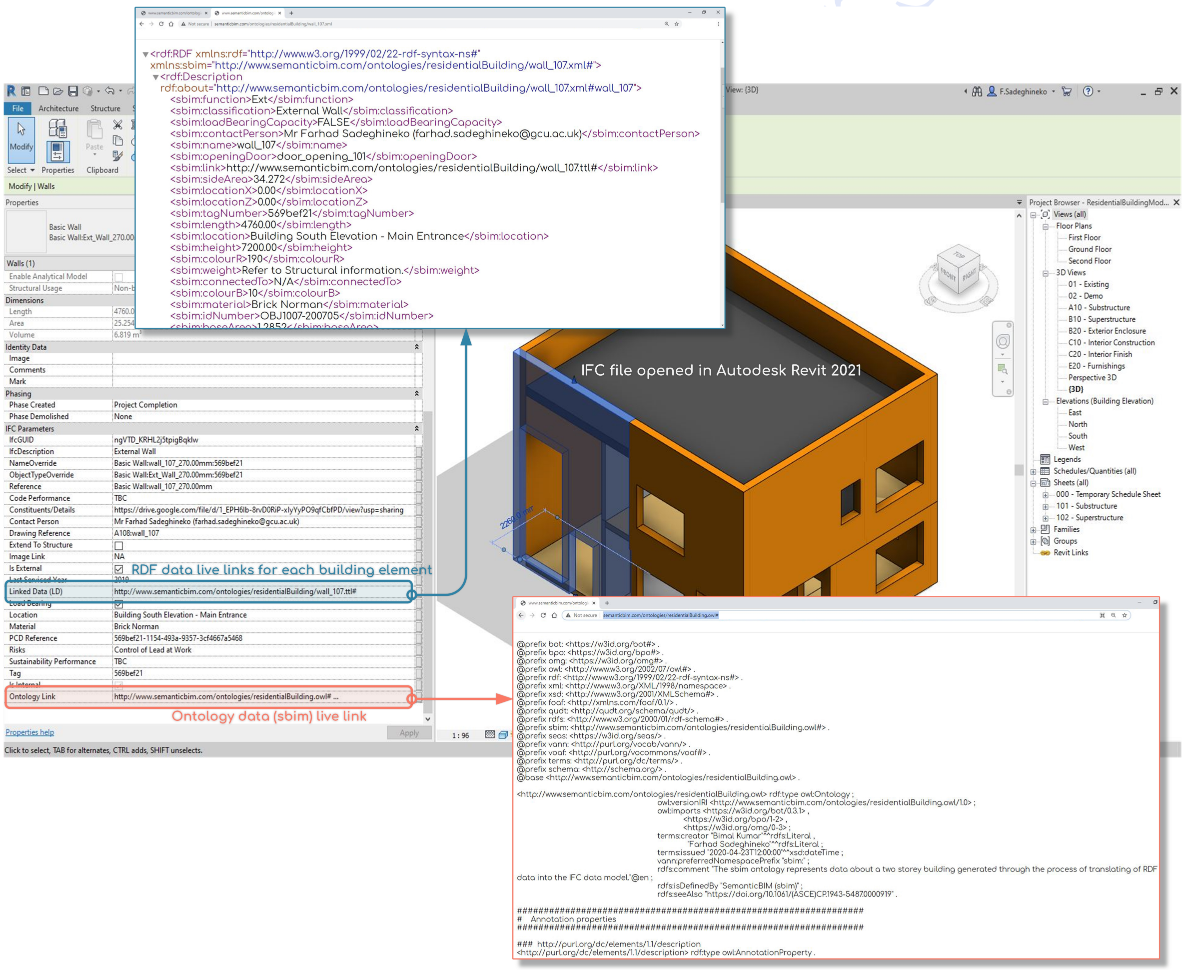

Fig. 6: RDF data live links embedded in the model for each building element (Blue) and the live link to the ontology version of projects data (Orange).

6. Framework validation

An example application has been implemented to validate the proposed framework. The example application presented in this section is about the data of a two-storey residential building initially generated by implementing the previously developed framework described in Section 4. After the data classification process, required ontologies are first imported into the base ontology (sbim). As illustrated in Table 1, other ontologies are indirectly imported into the base ontology by importing the first group of ontologies. The namespaces and prefixes of ontologies directly or indirectly imported into the project are listed in 1. Topologically, BOT ontology is used to extend the base ontology for describing the spatial relationships between building elements like zone, site, and building. OMG ontology is used to describe the geometrical data concerning the shape, size, relative position of objects, and corresponding properties like length, width, and height.

Table 1: Namespaces and prefixes of the referenced web ontologies and imported ontologies.

Prefixes	Name	Domain
bot	Building Topology Ontology	https://w3id.org/bot#
bpo	Building Product Ontology	https://w3id.org/bpo#
omg	Ontology for Managing Geometry	https://w3id.org/omg#
owl	Web Ontology Language	http://www.w3.org/2002/07/owl#
rdf	Resource Description Framework	http://www.w3.org/1999/02/22-rdf-syntax-ns#
xml	xml	http://www.w3.org/XML/1998/namespace
xsd	xsd	http://www.w3.org/2001/XMLSchema#
foaf	foaf	http://xmlns.com/foaf/0.1/
rdfs	Resource Description Framework Schema	http://www.w3.org/2000/01/rdf-schema#
sbim	sbim	http://www.semanticbim.com/ontologies/residentialBuilding.owl#
seas	Smart Energy Aware Systems Ontology	https://w3id.org/seas/
vann	vann	http://purl.org/vocab/vann/
voaf	voaf	http://purl.org/vocommons/voaf#
terms	terms	http://purl.org/dc/terms/
schema	schema	http://schema.org/
qudt	Quantities, Units, Dimensions and Type Catalog	http://qudt.org/schema/qudt

A graphical view of the topological relationships between building elements and their geometrical descriptions for the example application is illustrated in Figure 7. The sbim:Site_G1 is defined as an instance of the bot:Site class, which is a subclass of the bot:Zone class. The sbim:Site_G1 instance is connected to sbim:Building_G1 as a bot:Building class instance through the bot:hasBuilding object property. The sbim:Level_1 as a bot:Storey instance is linked to the sbim:Building_G1 instance by the bot:hasStorey object property. The relationships between the building instance and its corresponding elements are defined by the bot:Element class and related object properties. However, the geometrical description of instances is described by the OMG ontology. For example, the sbim:length as an omg:Geometry instance is a geometrical description of the sbim:wall_107 instance linked to the sbim:wall_107 instance through the omg:hasGeometry object property.

However, existing ontologies are designed based on specific functionalities (e.g. topology and geometry) and may not support all kinds of data. Hence, depending on the nature of the example application, new classes, object properties and data properties needed to be defined in the base ontology to provide fundamentals for describing all data represented in defined categories. As illustrated in Figure 8, the sbim:Project class has been created to describe geometrical and non-geometrical information using existing ontologies and new entries. For example, while the coordinate for the project origin point and the spatial dimensions of the BIM model is described by using the OMG ontology specifications, other associated information like the phase of the project (sbim:projectPhase) as an instance of sbim:Project is described through the use of new classes, object & data properties (e.g., sbim:hasPhase as an owl:ObjectProperty and sbim:hasLiteralValue as an owl:DatatypeProperty) which are specifically defined for the use in the base ontology.

Other ontologies like Building Product Ontology (BPO) are also used to extend the ontology created for the example application for enhancing the applicability of the data exchange process. The BPO ontology aims to describe a schematic representation of building products. In this regard, BPO ontology is used to describe the building components and their corresponding relationships and connections. As an example of the use of BPO ontology, following the wall and door opening instances illustrated in Figure 7, the inclusion of a door component data through the use of BPO ontology is shown in Figure 9. Moreover, the material of building elements and components is consequently described through the sbim:NonGeometry class, sbim:Material instance and sbim:hasMaterial object property defined in the base ontology.

https://doi.org/10.1108/CI-03-2021-0058

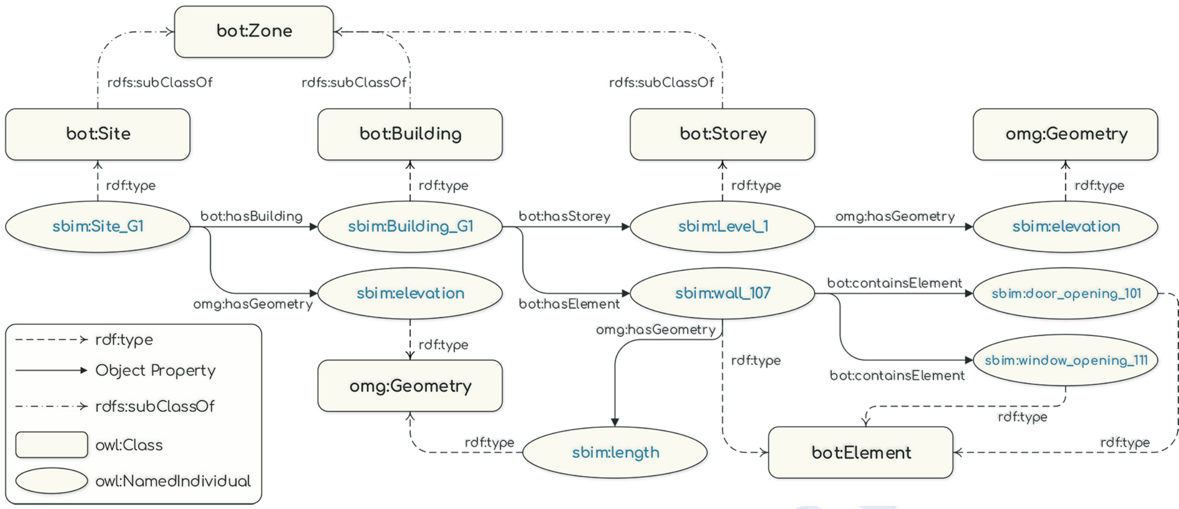

Fig. 7: Topological and geometrical relationships between building elements by using BOT and OMG ontologies.

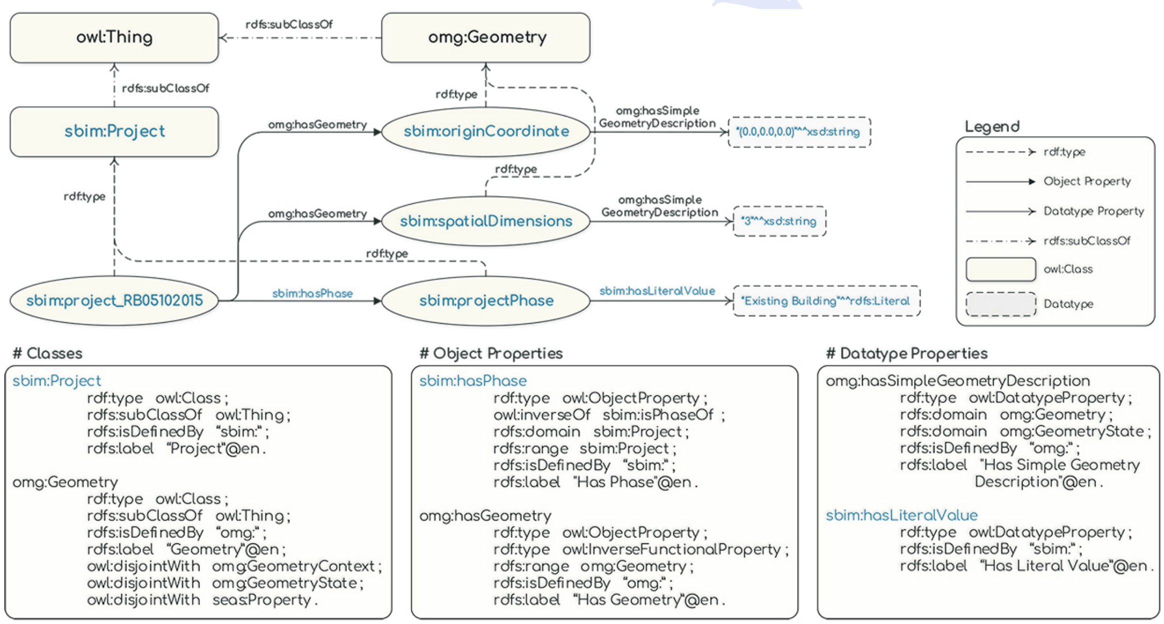

Fig. 8: The relationships between sbim classes and instances and imported ontologies.

7. Discussions

An appropriate parametric model that fits into a BIM-enabled design process, construction and O&M of assets should incorporate geometrical and non-geometrical data. Accordingly, an appropriate framework that aims to map building models containing all kinds of information required for O&M purposes should be capable of handling all kinds of data. The use of Semantic Web technologies and standards in structuring such a framework for generating semantically enriched models and facilitating the information exchange and interoperability within the building projects, in particular existing and retrofit assets that may or may not have appropriate 3D building models, can be an improvement in managing and manipulating the large-scale data involved in building projects. New and existing Web-based ontologies used in the framework proposed in this paper improve the process of generating enriched models and the exchange and interoperability of large-scale information. The information

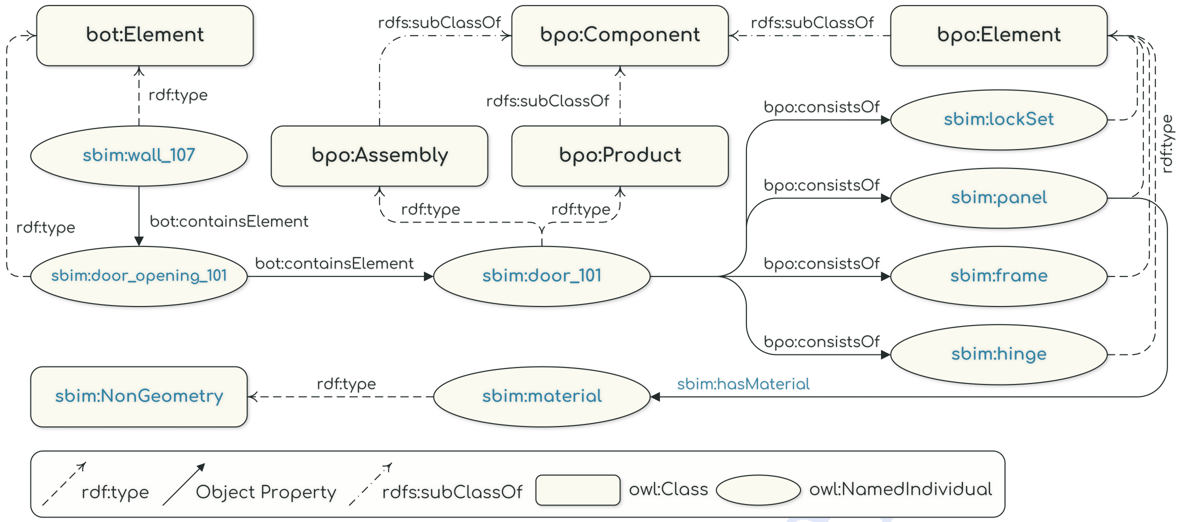

Fig. 9: The description of a door component using BPO ontology.

related to each building element is combined with the model, and individual RDF data can be accessed through the live links embedded in the model. The OWL version of the data containing all data distributed in RDF graphs can be accessed from inside and outside the model (Figure 6), which can also be used for further processing if required.

Concerning the reuse of information embedded in the BIM models, although some of the data can be exported as IFC and converted into the ifcOWL version using existing algorithms, some challenges are also involved in using the ifcOWL format. In essence, the ifcOWL is practically the web-based ontology version of the IFC data model, and it inherits the complexity of IFC specifications, making the data management and manipulation inefficient and ineffective (Beetz & Borrmann, 2018). One of the limitations of ifcOWL is that some of its modelling specifications are inconsistent with the Semantic Web best practices, like the definition of boolean and relations. The current condition of ifcOWL encompasses some syntactic structures that originate from the EXPRESS schema, making the ifcOWL ontology like the IFC data model complex, hard to understand, and inefficient in reasoning (Pauwels, Poveda-Villalón, Sicilia, & Euzenat, 2018; Schneider, Rasmussen, Bonsma, Oraskari, & Pauwels, 2018). The size of ifcOWL could be another limitation of this schema. It is created based on a single ontology containing all the IFC specifications, such as data types, scheduling, and units, making the ifcOWL usability more complex for users and developers that may require only a few concepts. Despite the challenges and limitations of reusing data combined with the model, the results show that the developed and proposed framework is promising and should be of interest to the various practices within the AM/FM domain.

8. Conclusion

The framework proposed in this paper focuses on facilitating the information exchange and interoperability for existing buildings by using Semantic Web technologies and standards, Web Ontology Language (OWL) in particular. In general, the framework consists of two main parts, including the framework previously developed for generating semantically enriched 3D retrofit models using RDF data and the second part focusing on the information exchange and interoperability for existing assets presented in this paper. The framework aims to use previously RDF graphs generated for each building element through a process of aggregating geometrical and non-geometrical data. As described in Section 3, the data was used to generate BIM models by translating RDF into the IFC data model. However, the approach presented in this paper focuses on the creation of a web ontology from the data represented in RDF graphs by using the applicability of new and existing ontologies within the AEC industry. Each of the existing ontologies focuses on a specific concept, e.g. the BOT ontology concerns the description of topological connections and spatial relationships between building elements without describing geometrical and non-geometrical data. However, one of the advantages of using web ontologies for storing,

https://doi.org/10.1108/CI-03-2021-0058

sharing, and reusing data is that ontologies can easily be extended and linked to other data sources structured based on LD principles. Moreover, new classes, sub-classes, object & datatype properties are included in the base ontology where required.

The semi-automated approach presented in this paper is a solution to the challenges and limitations involved in generating semantically enriched 3D retrofit models and the information exchange and interoperability for existing buildings. Semantic Web technologies facilitate data management and manipulation by simplifying data storage, share, and reuse. It also represents high-quality connected data and provides the basics for publishing linked data. The developed and proposed framework contributes to the AM/FM domain. It should be of interest to various AM/FM practices for existing buildings, such as a consistent and computable building information/knowledge management for design, construction and O&M of a building's life-cycle, the effectiveness and efficiency of the use of project information during the O&M of facilities, and prompt problem detection and resolution. The future work is to use other existing ontologies and integrate more data relating to different aspects of building projects which would contribute to other trends related to information exchange and interoperability, like the emergence of the Internet of Things (IoT) in smart buildings, building automation & monitoring, and building-related Information Technology (IT) infrastructure.

Acknowledgement

This is a substantially extended and enhanced version of the paper presented at The 20th International Conference on Construction Applications of Virtual Reality (CONVR 2020). We would like to acknowledge the editorial contributions of Professor Nashwan Dawood and Dr Farzad Rahimian of Teesside University in the publication of this paper.

References

Afsari, K., Eastman, C. M., & Castro-Lacouture, D. (2017). Javascript object notation (json) data serialization for ifc schema in web-based bim data exchange. *Automation in Construction*, *77*, 24–51. doi: 10.1016/j.autcon.2017.01.011

Banfi, F., Chow, L., Ortiz, M. R., Ouimet, C., & Fai, S. (2018). Building information modeling for cultural heritage: The management of generative process for complex historical buildings. In *Digital cultural heritage* (pp. 119–130). Springer. doi: 10.1007/978-3-319-75826-8_10

Barazzetti, L. (2016). Parametric as-built model generation of complex shapes from point clouds. *Advanced Engineering Informatics*, *30*(3), 298–311. doi: 10.1016/j.aei.2016.03.005

Barbau, R., Krima, S., Rachuri, S., Narayanan, A., Fiorentini, X., Foufou, S., & Sriram, R. D. (2012). Ontostep: Enriching product model data using ontologies. *Computer-Aided Design*, *44*(6), 575–590.

Beetz, J., & Borrmann, A. (2018). Benefits and limitations of linked data approaches for road modeling and data exchange. In S. I. & D. B. (Eds.), *Advanced computing strategies for engineering* (Vol. 10864, pp. 245–261). Springer. doi: 10.1007/978-3-319-91638-5_13

Beetz, J., Van Leeuwen, J., & De Vries, B. (2009). Ifcowl: A case of transforming express schemas into ontologies. *Ai Edam*, *23*(1), 89–101. doi: 10.1017/S0890060409000122

Bonduel, M., Oraskari, J., Pauwels, P., Vergauwen, M., & Klein, R. (2018). The ifc to linked building data converter-current status. In *6th linked data in architecture and construction workshop* (Vol. 2159, pp. 34–43). Retrieved from http://hdl.handle.net/1854/LU-8576838

Curry, E., O'Donnell, J., Corry, E., Hasan, S., Keane, M., & O'Riain, S. (2013). Linking building data in the cloud: Integrating cross-domain building data using linked data. *Advanced Engineering Informatics*, *27*(2), 206–219. doi: 10.1016/j.aei.2012.10.003

Dore, C., & Murphy, M. (2015). Historic building information modelling (hbim). In (p. 239-280). Handbook of Research on Emerging Digital Tools for Architectural Surveying, Modeling, and Representation, IGI Global. doi: 10.4018/978-1-4666-8379-2.ch007

Farias, M. T., Roxin, A., & Nicolle, C. (2015). Cobieowl, an owl ontology based on cobie standard. In *On the move to meaningful internet systems: Otm 2015 conferences* (pp. 361–377). Springer International Publishing. doi: 10.1007/978-3-319-26148-5_24

Götz, C. S., Karlsson, P., & Yitmen, I. (2020). Exploring applicability, interoperability and integrability of blockchain-based digital twins for asset life cycle management. *Smart and Sustainable Built Environment*.

Gui, N., Wang, C., Qiu, Z., Gui, W., & Deconinck, G. (2019). Ifc-based partial data model retrieval for distributed collaborative design. *Journal of Computing in Civil Engineering*, *33*(3), 04019016. doi: 10.1061/(ASCE)CP.1943-5487.0000829

Hamdan, A.-H., & Kozak, T. (2019, May). *Brige topology ontology.* Retrieved 2019-12-12, from https://wisib.de/ontologie/brot/

Hayne, G., Kumar, B., & Hare, B. (2014). The development of a framework for a design for safety bim tool. In *Computing in civil and building engineering (2014)* (pp. 49–56). American Society of Civil Engineers. doi: 10.1061/9780784413616.007

Klein, L., Li, N., & Becerik-Gerber, B. (2012). Imaged-based verification of as-built documentation of operational buildings. *Automation in Construction*, *21*, 161–171. doi: 10.1016/j.autcon.2011.05.023

Kumar, B. (2016). *A practical guide to adopting bim in construction projects*. Whittles Publishing Limited.

Lee, D.-Y., Chi, H.-l., Wang, J., Wang, X., & Park, C.-S. (2016). A linked data system framework for sharing construction defect information using ontologies and bim environments. *Automation in Construction*, *68*, 102–113. doi: 10.1016/j.autcon.2016.05.003

Molinero Sánchez, J. G., Gómez-Blanco Pontes, A., & Rivas López, E. J. (2019). Bim methodology in heritage management. In C. L. Marcos (Ed.), *Graphic imprints* (pp. 835–843). Cham: Springer International Publishing. doi: 10.1007/978-3-319-93749-6_67

Oliver, S., Seyedzadeh, S., Rahimian, F., Dawood, N., & Rodriguez, S. (2020). Cost-effective as-built bim modelling using 3d point- clouds and photogrammetry. *Current Trends in Civil and Structural Engineering - CTCSE*, *4*(5). doi: 10.33552/CTCSE.2020.04.000599

Pauwels, P., McGlinn, K., Törmä, S., & Beetz, J. (2018). Linked data. In A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.), *Building information modeling: Technology foundations and industry practice* (pp. 181–197). Cham: Springer International Publishing. doi: 10.1007/978-3-319-92862-3_10

Pauwels, P., Poveda-Villalón, M., Sicilia, Á., & Euzenat, J. (2018). Semantic technologies and interoperability in the built environment. *Semantic Web*, *9*(6), 731–734.

Pauwels, P., & Terkaj, W. (2016). Express to owl for construction industry: towards a recommendable and usable ifcowl ontology. *Automation in Construction*, *63*, 100–133. doi: 10.1016/j.autcon.2015.12.003

Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., De Meyer, R., Van de Walle, R., & Van Campenhout, J. (2011). A semantic rule checking environment for building performance checking. *Automation in Construction*, *20*(5), 506–518. doi: 10.1016/j.autcon.2010.11.017

Pour Rahimian, F., Seyedzadeh, S., Oliver, S., Rodriguez, S., & Dawood, N. (2020). On-demand monitoring of construction projects through a game-like hybrid application of bim and machine learning. *Automation in Construction*, *110*, 103012. doi: 10.1016/j.autcon.2019.103012

Quattrini, R., Malinverni, E., Clini, P., Nespeca, R., & Orlietti, E. (2015). From tls to hbim. high quality semantically-aware 3d modeling of complex architecture. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *40*(5), 367–374. doi: 10.5194/isprsarchives-XL-5-W4-367-2015

Rasmussen, M. H., Hviid, C. A., & Karlshøj, J. (2017). Web-based topology queries on a bim model. In *Ldac2017–5th linked data in architecture and construction workshop.* Dijon, France.

Rasmussen, M. H., Pauwels, P., Lefrançois, M., Schneider, G. F., Hviid, C. A., & Karlshøj, J. (2017, Nov). Recent changes in the building topology ontology. In *Ldac2017 - 5th linked data in architecture and construction workshop.* Dijon, France.

Sadeghineko, F., & Kumar, B. (2020). Development of semantically rich retrofit 3d models. *Journal of Computing in Civil Engineering*, *34*. doi: 10.1061/(ASCE)CP.1943-5487.0000919

Sadeghineko, F., Kumar, B., & Chan, W. (2018). A semantic web-based approach for generating parametric models using rdf. In I. Smith & B. Domer (Eds.), *Advanced computing strategies for engineering* (Vol. 10868, pp. 361–377). Springe. doi: 10.1007/978-3-319-91638-5_20

Sadeghineko, F., Kumar, B., & Chan, W. (2019). Employment of semantic web technologies for capturing comprehensive parametric building models. In *Advances in informatics and computing in civil and con-*

https://doi.org/10.1108/CI-03-2021-0058

struction engineering (pp. 111–122). Springer. doi: 10.1007/978-3-030-00220-6_14

Sayah, Z., Kazar, O., Lejdel, B., Laouid, A., & Ghenabzia, A. (2020). An intelligent system for energy management in smart cities based on big data and ontology. *Smart and Sustainable Built Environment*.

Schevers, H., & Drogemuller, R. (2005). Converting the industry foundation classes to the web ontology language. In *2005 first international conference on semantics, knowledge and grid* (pp. 73–73).

Schneider, G. F., Rasmussen, M. H., Bonsma, P., Oraskari, J., & Pauwels, P. (2018). Linked building data for modular building information modelling of a smart home. In J. Karlshoj & R. Scherer (Eds.), *Ework and ebusiness in architecture, engineering and construction* (pp. 407–414). CRC Press.

Seyedzadeh, S., Rahimian, F. P., Glesk, I., & Kakaee, M. H. (2017). Variable weight spectral amplitude coding for multiservice ocdma networks. *Optical Fiber Technology*, *37*, 53-60. doi: https://doi.org/10.1016/j.yofte.2017.07.002

Seyedzadeh, S., Rahimian, F. P., Oliver, S., Glesk, I., & Kumar, B. (2020). Data driven model improved by multi-objective optimisation for prediction of building energy loads. *Automation in Construction*, *116*, 103188.

Shalabi, F., & Turkan, Y. (2016). Ifc bim-based facility management approach to optimize data collection for corrective maintenance. *Journal of Performance of Constructed Facilities*, *31*(1), 04016081. doi: 10.1061/(ASCE)CF.1943-5509.0000941

Sheikhkhoshkar, M., Pour Rahimian, F., Kaveh, M. H., Hosseini, M. R., & Edwards, D. J. (2019). Automated planning of concrete joint layouts with 4d-bim. *Automation in Construction*, *107*, 102943. doi: https://doi.org/10.1016/j.autcon.2019.102943

Son, H., & Kim, C. (2016). Automatic segmentation and 3d modeling of pipelines into constituent parts from laser-scan data of the built environment. *Automation in Construction*, *68*, 203–211. doi: 10.1016/j.autcon.2016.05.01

Tang, P., Huber, D., Akinci, B., Lipman, R., & Lytle, A. (2010). Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. *Automation in construction*, *19*(7), 829–843. doi: 10.1016/j.autcon.2010.06.007

Terkaj, W., & Pauwels, P. (2017). A method to generate a modular ifcOWL ontology. In *Proceedings of the joint ontology workshops 2017 episode 3: The tyrolean autumn of ontology* (Vol. 2050, p. 12). Retrieved from http://hdl.handle.net/1854/LU-8578707

Terkaj, W., Schneider, G. F., & Pauwels, P. (2017). Reusing domain ontologies in linked building data: the case of building automation and control. In *Proceedings of the joint ontology workshops 2017 episode 3: The tyrolean autumn of ontology* (Vol. 2050, p. 12).

Thomson, C., & Boehm, J. (2015). Automatic geometry generation from point clouds for bim. *Remote Sensing*, *7*(9), 11753–11775. doi: 10.3390/rs70911753

Tran, H., Khoshelham, K., Kealy, A., & Díaz-Vilariño, L. (2018). Shape grammar approach to 3d modeling of indoor environments using point clouds. *Journal of Computing in Civil Engineering*, *33*(1), 04018055. doi: 10.1061/(ASCE)CP.1943-5487.0000800

Uggla, G., & Horemuz, M. (2018). Geographic capabilities and limitations of industry foundation classes. *Automation in Construction*, *96*, 554–566. doi: 10.1016/j.autcon.2018.10.014

Volk, R., Stengel, J., & Schultmann, F. (2014). Building information modeling (bim) for existing buildings - literature review and future needs. *Automation in construction*, *38*, 109–127. doi: 10.1016/j.autcon.2013.10.023

Wagner, A., Bonduel, M., Pauwels, P., & Uwe, R. (2019). Relating geometry descriptions to its derivatives on the web. In *2019 european conference on computing in construction* (pp. 304–313). doi: 10.35490/ec3.2019.146

Wagner, A., & Rüppel, U. (2019). Bpo: The building product ontology for assembled products. In *Proceedings of the 7th linked data in architecture and construction workshop (ldac 2019), lisbon, portugal* (p. 12).

Wang, C., Cho, Y. K., & Kim, C. (2015). Automatic bim component extraction from point clouds of existing buildings for sustainability applications. *Automation in Construction*, *56*, 1–13. doi: 10.1016/j.autcon.2015.04.001

Žáček, M., & Janošek, M. (2017). Sbonto: Ontology of smart building. *Far East Journal of Electronics and Communications*, *17*(5), 1101–1109.

Zhang, G., Vela, P. A., Karasev, P., & Brilakis, I. (2015). A sparsity-inducing optimization-based algorithm for planar patches extraction from noisy point-cloud data. *Computer-Aided Civil and Infrastructure Engi-*

neering, *30*(2), 85–102. doi: 10.1111/mice.12063